Morphology Changes Affected by Sediment Concentration and River Flow in Meandering Channels of the Bengawan Solo River

Ria Soemitro[1], Toshifumi Mukunoki[2], Mahendra Maulana[1], Robby Soetanto[3], Dwa Desa Warnana[1], and Trihanyndio Satrya[1]

[1]Institut Teknologi Sepuluh Nopember
[2]Kumamoto University
[3]Loughborough University

August 16, 2022

Abstract

Increases in critical land in the Bengawan Solo River Basin contribute to floods and severe damage to infrastructures along the river channel. Additionally, the occurrence of excessive erosion is a source of sediment materials, especially at meandering sections. Riverbank erosion destabilises dykes and sediment deposition decrease capacity, thereby resulting in floods (especially during rainy seasons). Although both phenomena can be evaluated by observing flow velocity and sediment concentration, there is a paucity of field investigations on parameters that affect erosion under dry and rainy seasons. This study investigates the aforementioned parameters and contrasts circumstances during dry and rainy seasons by presenting relevant information on sediment quantity and flow velocity. The results indicate that sediment concentration at the outer banks of the flow path significantly exceeds that at the inner banks, thereby indicating significant occurrence of erosion. Further examination of riverbed material suggests that the interaction between sediment concentration and flow velocity, especially in meandering segments, can provide an estimate of the erosion rate and the change in the morphology of the alluvial river. Sediment concentration is correlated with seasonal conditions such that sediment concentration during the rainy season is approximately five times that in the dry season. This clarifies that more significant river morphology changes occur during peak seasons. Further, the results of the study can be used in river dynamic process prediction, especially in alluvial streams or in soft soil with properties similar to that of alluvial streams.

Morphology Changes Affected by Sediment Concentration and River Flow in Meandering Channels of the Bengawan Solo River

Ria Asih Aryani Soemitro [1,*], Toshifumi Mukunoki[2], Mahendra Andiek Maulana [3], Robby Soetanto [4], Dwa Desa Warnana[5], and Trihanyndio Rendy Satrya[6]

[1] Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Indonesia

[2] Department of Civil and Environmental and Architecture, Faculty of Advanced Science and Technology, Kumamoto University, Japan

[3] Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Indonesia

[4] School of Architecture, Building and Civil Engineering, Loughborough University, United Kingdom

[5] Geophysical Engineering Department, Institut Teknologi Sepuluh Nopember, Indonesia

[6] Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Indonesia

* ria@ce.its.ac.id

Received: date; Accepted: date; Published: date

Acknowledgements

This study was funded by Research Grant Batch 2 2015–2016 from the Directorate General of Higher Education–Indonesian Ministry of Education and Culture and the US National Academy of Sciences (NAS) [grant number AID-OAA-A-11-00012, Sub-Grant Number PGA 2000005020] 2014–2018. Primary data collection was supported by Institut Teknologi Sepuluh Nopember-Surabaya, Bengawan Solo River Authority Bureau (Balai Besar Wilayah Sungai Bengawan Solo-BBWS Bengawan Solo) and the Ministry of Public Works and Public Housing of the Republic of Indonesia. This research was partially funded by the Indonesian Ministry of Research and Technology/National Agency for Research and Innovation and the Indonesian Ministry of Education and Culture, under the World Class University Program managed by Institut Teknologi Bandung.

Abstract

Increase in critical land in the Bengawan Solo River basin has contributed to floods and severe damage to infrastructure along the river channel. Additionally, the occurrence of excessive erosion is a source of sediment materials, especially in meandering sections. Riverbank erosion destabilises river dykes and sediment deposition decreases river capacity, thereby resulting in floods (especially during rainy seasons). Although both phenomena can be evaluated by observing flow velocity and sediment concentration, there is a paucity of field investigations on parameters that affect erosion during dry and rainy seasons. This study investigates the aforementioned parameters and contrasts circumstances during dry and rainy seasons by presenting relevant information on sediment quantity and flow velocity. The results indicate that the sediment concentration at the outer banks of the flow path significantly exceeds that at the inner banks, thereby indicating a significant occurrence of erosion. Further examination of riverbed material suggests that the interaction between sediment concentration and flow velocity, especially in meandering segments, can provide an estimate of the erosion rate and the change in the morphology of the alluvial river. Sediment concentration is correlated with seasonal conditions such that sediment concentration during the rainy season is approximately five times higher than that during the dry season. This indicates that more significant river morphology changes occur during peak seasons. Furthermore, the results of the study can be used in river dynamic process prediction, especially in alluvial streams or in soft soil with similar properties to alluvial streams.

Keywords: Bengawan Solo River, alluvial river, curved channel, erosion, sediment concentration

1. Introduction

Erosion in river channels have previously been examined to assess the effect of flow on the riverbanks, mainly in the outer section of the meandering channels (Konsoer et al., 2016). The results confirm that significant erosion occurs around this area, especially during floods. Erosion of the riverbank or stream bed causes a shift of sediments in the river channel, resulting in changes in river morphology over time (Rinaldi and Darby, 2007). Erosion of river streams can endanger the natural environment, built infrastructure, and living organisms (including human life). Accretion of the river channel is related to land losses and changes in the Earth's surface. The fundamental theory related to river dynamics suggests that erosion and deposition are the primary factors in the processes of channel alteration. Channel meandering and shifting occur when water flow frequently fluctuates in the area. Furthermore, erosion at the outer side of the curved sections is the most important factor affecting changes in river geometry in meandering channels (Uddin and Rahman, 2012).

Sediment transport is an indicator of erosion that can be easily observed in river flow represented by turbid water. Sediment transport can cause horizontal channel movements and create meandering channels that are mostly generated due to bank erosion. Simultaneously, channel vertical transformation is indicated by aggradation along the riverbed (Abate et al., 2015). Both horizontal and vertical transformations are fundamental to the dynamic processes of river morphology, especially in alluvial rivers with frequent occurrences of sediment transport. Changes in river morphology are determined by erosion and deposition processes, and thus channel alteration can be evaluated using the erosion rate, deposition rate, and flow discharge (Alekseevskiy et al., 2008). Erosion and deposition refer to the movement of sediment mass due to river flow. Deposition occurs when the sediment particles reach a settling velocity state. Additionally, low flow discharge and flow paths can trigger deposition. Low flow discharge is caused due to a decrease in flow velocity that causes sediment particles to descend. Additionally, the flow path change (which occurs in meandering sections) can significantly decrease the flow velocity. Therefore, the flow velocity of a meandering channel moves both in the vertical and lateral directions of the flow stream. Previous studies have indicated that outer bends tend to exhibit incised channel geometry associated with high flow velocity (Dugué et al., 2013). Conversely, shallow riverbeds can be observed around the inner bends. This phenomenon suggests that the magnitude of flow velocity and erosion, or deposition, are strongly connected. Hence, the flow condition is also affected by climate change (Nadal-Romero et al., 2008; Unverricht et al., 2014). The rainfall that accumulates in river flow significantly changes this phenomenon. Sediment concentration (indicating the erosion process) decreases during low flow and increases significantly during floods (Chanson et al., 2011; Liu et al., 2014). An evident correlation between the flow and sediment concentration in curved channels was observed in the Danube and Magdalena Rivers in Romania and Colombia, respectively (Jugaru Tiron et al., 2009; Higgins et al., 2016). On the other hand, sediment concentration is one of the most important parameters in river morphology change. The effect of suspended material from mud volcanoes on the Porong River provides approximately 10 cm/year of riverbed accretion (Sidik et al., 2016). Furthermore, rapid increases in sediment concentration produce sediment deposit mass at riverbanks, indicating an early process of river morphology dynamics (Juez et al., 2018). It also confirmed that the decrease in flow discharge followed by suspended sediment reduction in the Middle Volda River basin may have slowed down the morphology change (Gusarov, 2020). Hence, the sediment characteristics and stream flow play a key role in the morpho-dynamics in natural channels.

The aim of this study is to evaluate the flow and sediment concentration in meandering sections of the Bengawan Solo River. Based on a field investigation, the results suggest that flow conditions are different from those in previous studies, where the highest flow velocity occurred in the inner as opposed to the outer bends (Alekseevskiy et al., 2008 and Dugué et al., 2013). In this study, the results indicate that the irregular shapes of the outer banks (due to erosion) increase turbulence in the river flow. Hence, excessive scouring occurs, as evidenced by the suspended sediment concentration. The differences between the flow velocity and suspended sediment concentration in the inner and outer curved channels correspond to a key factor in influencing the alluvial river dynamic process. This study presents findings based on primary data taken from curved river sections, where severe erosion and river embankment failure frequently occur on the outer side. It is already known that erosion rate calculations are based only on values measured at a particular time, in a particular condition. Additionally, erosion rate prediction by itself does not provide an accurate result. Given the fluctuation in field conditions, this study attempts to propose a better solution for calculating the erosion rate. The relationship between the river discharge and suspended sediment concentration (SSC) has been observed for the Sukhaya Elizovskaya River, Russia (Mouri et al., 2014). More notably, the highest SSC value was reached during floods. Another study showed that maximum sediment concentrations, that also contains high flow velocity, follow the peak discharge (Rodríguez-Blanco et al., 2020). Furthermore, the correlation among flow velocity, Reynolds stress, and SSC exhibits a linear function during the flood (Reungoat et al., 2019). Hence, this study contributes to the literature on the effect of flow velocity and SSC (as an erosion rate indicator) on the river meandering process.

Sediment concentration measurements are associated with turbulence characterisations conducted at high frequencies in the undular tidal bore of the Garonne River, France (Chanson et al., 2011). A study showed that the sediment concentration around the riverbed area was 2.8 times higher than that at the water's surface (Liu et al., 2014). Extant studies have focused on the relationship between sediment concentration and bed shear stress and indicated that the bed shear stress significantly affects sediment concentration, thereby indicating the origin of the erosion process (Wang and Lu, 2010).

The Bengawan Solo River is located between 110°18' and 112°45' E longitude and 6°49' and 8°08' South Latitude. The total length of the main river is approximately 600 km, and it flows from the mountainous area in Central Java to the Java Sea in East Java Province. The river basin covers an area of approximately 16,000 km^2. It is classified as an alluvial river (El Mountassir et al., 2011). Hence, sediment transport significantly affects the alterations in river morphology through erosion and deposition processes. The research site is located at Kanor Village, Bojonegoro District, East Java Province, which has a distance of approximately 500 km from the upstream area. This section of the river features a unique curvature of the stream flow with large and small meandering channels. The value of stream sinuosity at the study location is 2.14, which indicates a high possibility of lateral migration in this section. The channel width is approximately 200 m with an average bed slope of 0.20%. The on-site field work was performed in a meandering channel that exhibits maximum and minimum curvature radii of 1,037 m and 903 m, respectively. Scoured areas developed at the outer bend of the stream flow, while deposition occurred around the inner bend areas. The severe erosion process broke the river dykes on both sides. This phenomenon occurred between 1974 and 1995 (Soemitro and Asmaranto, 2016). The erosion on the riverbank destabilized the river dyke, and deposition on the riverbed decreased the river capacity, leading to flooding in the rainy season. Both phenomena can be evaluated by observing the flow velocity and sediment concentration. However, there is a paucity of field investigations to address these aspects.

The climate in the area can be distinguished into dry and rainy seasons. The rainy season is the period from December to March. The west–northwest monsoon carries humid air and causes high precipitation. Furthermore, the east–southeast monsoon that occurs between May and September exhibits less humidity. Hence, the dry season occurs during this period (Hoekstra et al., 1988). The average annual rainfall is 2000 mm/year, while the lowest and highest rainfall values are 1510 and 2990 mm/year, respectively.

The flow discharge is extremely different between dry and rainy seasons, with maximum and minimum average flow discharges of 800 m^3/s and 5 m^3/s, respectively. In the dry season, significant damage may not occur because the flow discharge is low. Conversely, the rainy season causes a significantly greater flow, which can lead to adverse conditions. Floods, infrastructure failures, and collapses of riverbanks are common occurrences during the rainy season. Additionally, the interaction between river materials and flow results in massive erosion and creates a source for sediment transport.

2. Materials and Methods

The field work was performed at approximately 1000 m from the meandering section and consisted of three cross-sections of observation points. Each cross-section was separated at approximately 500 m with cross-section II located at the centre of the meandering. The measurements were scheduled every two weeks starting from January until August. The measurement period represents two major climates in the Bengawan Solo River basin, namely the rainy season between January and March and the dry season between April and August. Field data was collected at the Bojonegoro section of the Bengawan Solo River, which corresponds to the river's curved section, as shown in Figure 1. Continuous observations were conducted at the meandering channel to obtain the flow velocity and sediment data.

The flow velocity was recorded using an automatic current meter (Marsh-McBirney Model 21, US). The specification of the current meter corresponded to a magnetic type that could measure up to 20 m of depth with an error tolerance of approximately 0.5%. The components of the current meter consist of a 25 kg stabiliser, magnetic sensor, 20 m cable and rope, and digital recorder. At each cross-section, the flow velocities were measured every 20 m of the river width. Specifically, the vertical flow velocity distributions were measured using the three-point method, i.e., 0.2 h, 0.6 h, and 0.8 h, where $h$denotes the water depth measured from the surface of the water (Maulana et al., 2018). Water samples were obtained to measure the SSCs. The SSC was collected using a modified bottle sampler that was locally designed to satisfy the requirements of sediment concentration sampling. This apparatus was equipped with a 600 mL bottle as per the minimum sample volume requirement stated in ASTM Standard D-3977. Subsequently, the water samples were in a laboratory to obtain SSC values. The water samples containing the sediment were dried to measure the dissolved solid concentration. Additionally, riverbed samples were collected to determine the sediment grain size. Stream bed materials were collected from the outer side of the curved channel when erosion occurred. The riverbed material sample was obtained using a bottom grab. The bottom grab is a simple equipment that can lift sediment material from the riverbed. The instrument consists of two large buckets that are connected by two metal rods. The device automatically closes when it reaches the riverbed and grabs the sediment material in the buckets. The sediment grab capacity is approximately 0.05 m^3, which is adequate to obtain a minimum sample for gradation analysis. Furthermore, the grain size distribution of streambed and bank materials were obtained from Sieve and Hydrometer test analyses, and thus riverbank resistance can be analysed in terms of riverbed material characteristics.

3. Results

3.1. Flow discharge and suspended sediment concentration

From January through August, the average flow discharge was 230.64 m^3/s with minimum and maximum values corresponding to 24.74 and 445.83 m^3/s, respectively. As shown in Figure 2, the flow discharge decreased from the rainy season to the dry season. The peak season where the flow was the highest occurred between January and March. The flow significantly decreased during February because the rainfall intensity did not significantly affect the flow. However, the conditions changed significantly in March, given that the river flow attained maximum discharge, thereby indicating the continuation of the rainy season. After March, the flow continuously decreased until August, thereby implying the absence of water supply from upstream sources.

3.2 Flow velocity and suspended sediment concentration

Figure 3 shows the flow velocity and SSC of the inner and outer bends at each measurement point. It is noted that in cross-section III, the flow changed from left to right, as shown in Figure 1. Figure 3(a) shows the average flow velocity at cross-section I, and A and B denote the outer and inner bends, respectively.

The flow velocity at the outer bend ranged between 0.0275 and 1.075 m/s while the inner bend ranged between 0.04 and 1.05 m/s, which was 2% lower when compared to that that at the outer bend during the peak rainy season (January–February). The highest difference in the flow velocity between the inner and outer bends occurred during February and March with flow velocities corresponding to 1.075 and 0.470 m/s for the outer and the inner bend, respectively. Figure 3(b) shows the average flow velocity conditions at cross-section II. The pattern was slightly different at cross-section I, where the inner bend exhibits a significantly higher flow velocity when compared to that in the outer bend from January to May. The inner bend flow velocity values ranged between 0.040 m/s and 0.705 m/s, while the outer bend flow velocity ranged between 0.026 m/s and 0.187 m/s. This trend changed considerably after May when the outer bend velocity slightly exceeded that at the inner bend. This is potentially because the outer bend velocity rebounds in response to the seasonal transition. Figure 3(c) shows the average flow condition of cross-section III. From January to April, the flow velocity at the inner bend (0.285–0.737 m/s) exceeded that at the outer bend (0.247–0.72 m/s). Based on the flow velocity conditions, the river bend experienced two major circumstances that were generated by the rainy and dry seasons. During the rainy season, the maximum flow velocity at cross-section I occurred at the outer bend, while the highest flow velocities were observed at the inner bend at cross-sections II and III. Additionally, the trend completely shifted during the seasonal transition period from April to May. The changes in the flow magnitude at cross-section I were such that the value at the outer bend became slightly lower than that at the inner bend. Conversely, cross-sections II and III reveal an opposite trend in which the outer bend area dominates the inner bend area in terms of flow velocity from April to May. The difference between the flow velocities at the outer and inner bends corresponded to an average of 18% and 10% at cross-sections II and III, respectively. The condition illustrates the pattern of the flow force differences between the inner and outer bends, which increases the tendency of the erosion process in the meandering segment.

To understand erosion and channel alteration processes in the meandering river, the SSC of the Bengawan Solo River should be analysed to determine sediment quantities, which is a good indicator of the rate of erosion development at the study site. Figure 3 also shows the SSC conditions at the three cross-sections. The SSC displays a trend similar with the flow velocity magnitude. In the rainy season, the outer bend at cross-sections I and III produced a higher quantity of suspended sediments. On average, the outer bends at cross-sections I and III contained sediments with concentrations that were 2% and 6%, respectively, higher than that of the corresponding inner bends. Conversely, the inner bend at cross-section II produced a sediment quantity that was 31% higher than that at the outer bend. In the dry season, the difference in sediment concentration between the inner and outer bends at cross-section III was evident. The SSC appeared to accumulate at the inner bend, thereby resulting in a 10.3% increase over that in the outer bend.

The correlation between SSC and average flow velocity at the three cross-sections is shown in Figure 4. The Pearson correlation test was used to analyse the relationship between SSC and flow velocity. The correlation values (r) were 0.753, 0.713, and 0.530 for cross-sections I, II, and III, respectively. Based on the correlation test results, the SSC values were strongly related to the flow magnitude in cross-sections I and II, where a higher flow velocity can generate higher sediment concentration. Additionally, SSC and the flow velocity of cross-section III exhibited a moderate correlation, thereby indicating that, in addition to flow velocity, other parameters also affect sediment concentration.

3.3 Effect of turbulence on the flow velocity and suspended sediment concentration

Tiron Duţu et al. (2014) and Dugué et al. (2013) concluded that a higher sediment concentration occurs around the outer bend when compared to that in the inner bend, which is characterised by high flow velocity. However, the Bengawan Solo River exhibits a different phenomenon pertaining to flow velocity and sediment concentration. The aforementioned findings indicate that the flow velocity magnitude is slightly different between the outer and inner bends, with the exception of cross-section II. The anomaly is observed during the rainy season and can be affected by the turbulent flow conditions indicated by the Reynolds number, as shown in Figure 5. This shows that the correlation between the Reynolds number and average flow velocity around the inner bend (R-square value of 0.89) exceeds that at the outer bend (R-square value of 0.72). Additionally, the Reynolds number implies that the inner bend exhibits a steadier flow when compared to that at the outer bend. Hence, the flow velocity and SSC around the inner bend exhibited a better correlation when compared to that at the outer bend. Simultaneously, the turbulent flow regime generated the secondary flow, which led to an irregular flow path in the specific geometry of the channel (such as around the curved section). However, the use of the SSC as an erosion indicator explains the highly dynamic behaviour in the meandering channel wherein a higher sediment concentration is produced at the outer bend, especially under the effect of high flow velocity.

3.4 Channel resistance and centrifugal acceleration

A correlation exists between the average flow velocity and centrifugal acceleration and indicates that the value at the outer bend tends to exceed that at the inner bend area. Thus, the increased dynamic behaviour at the outer bend is because of the effect of centrifugal force at the curved channel. An increase in the radius at the outer bend increases the centrifugal acceleration and generates higher forces. As shown in Figure 6, the higher curves of the average flow velocity and centrifugal acceleration at the outer bend tend to produce higher sediment concentration when compared to those at the inner bend of the meandering channel.

In a natural channel, the flow resistance is determined by a set of factors that can change the direction or magnitude of the flow velocity. The resistance in the channel is denoted by Ω (Dingman, 2009) and represents the ratio between the river channel material and the shear flow. The correlation between channel resistance and shear stress explains the sediment movement phenomenon. As shown in Figure 7, the resistance tends to exhibit a negative correlation with the shear stress. The resistance at the outer and inner bends in the meandering channel decreases when the shear stress increases. This implies that the sediment material loses resistance due to the accumulation of shear stress and an increase in velocity magnitude. The flow resistance ranged between 0.0325 and 0.043, while the shear stress ranged between 25 and 175 N/m^2.

The shear stress is an indicator of the channel resistance relative to the flow force, which contributes to the sediment content in the flow. High shear stress implies the action of a high flow force on the stream bed. Therefore, there is a high possibility of sediment particle transport from the original position to the deposition area. Thus, high shear stress is an indicator of an erosive area in the channel stream. This suggests a relationship between a high sediment concentration and high shear stress value. Additionally, the critical shear stress as the sediment material strength is used to determine the minimum shear stress required to move the sediment material. The condition of the material of the riverbank sediment relative to the flow velocity at the study site can be evaluated using the Hjulstrom diagram. The mean grain size (d_{50}) of the riverbank sediment material and flow velocity overlaid on the diagram are shown in Figure 8. Based on the flow velocity and grain size at the study site, the sediment material at the riverbank is placed in the transport and erosion zone. This confirms the previous analysis that the river channel potentially changes due to excess shear stress and sediment transport process. Specifically, the possibility of erosion at the study site is approximately 40%, which is generated by the flow velocity in the range of 0.3–1.0 m/s. Additionally, the transported sediment material is observed between 0.01–0.30 m/s and implies that sediment transport only requires 25% of the eroded velocity.

The effect of SSC distribution is from river profile outlines. Figure 9 shows the diversification at three observation points at the site location. The lateral distribution of SSC in the cross-sectional channel indicates that the inner flow path contains the highest sediment quantity when compared to the outer and middle areas of the cross-section. This implies that the inner river bend developed into a deposition area with respect to the amount of sediment load accumulation that exists in this part. On average, the inner and outer bend comprise 37% and 30% of sediment quantity, respectively. The distribution provides the comprehensive condition of the sediment supply on each flow path that plays an essential role in river morphology development. A high sediment load in the inner part is expected to be the main source of sedimentation material supply. Specifically, the accumulation of sediment material in the inner bend settles as deposition that leads to the accretion of the riverbed level. Conversely, the outer bend flow path exhibits the lowest sediment quantity and is potentially short of sediment supply.

From the viewpoint of river morphology, the sediment distribution explains the pattern in which river geometry is formed. Decreases in the sediment concentration in the outer bend indicate that the occurrence of sediment deposition is not as significant as that in the inner part. Hence, the increment rate of the inner riverbed exceeds that of the outer bend. Thus, the inner bend slopes of cross-sections I, II, and III are 0.13%, 0.09%, and 0.05%, respectively. Additionally, the outer bend slope tilts are steeper than those of the inner bend with slope values corresponding to 0.19%, 0.58%, and 0.08% for cross-sections I, II, and III, respectively. It is noted that the outer bend slope in cross-section II is the steepest, and this corresponds to the most eroded part, when comparing the other two sections. Therefore, the geometry profile of river cross-sections is inclined towards the inner side and results in a deep pool in the outer bend, as shown in Figure 1.

4. Conclusions

In this study, the critical shear stress, which is an indicator of stream bed material resistance relative to the flow force, was confirmed to be lower at the outer bend when compared to that at the inner bend. The flow velocity and SSC were considered good indicators of erosion in the Bengawan Solo River and were investigated under two circumstances: rainy and dry seasons. Specifically, SSC during the rainy season indicated that sediment materials were concentrated around the outer bend, when compared to that at the inner bend, especially at cross-sections I and III. This implies that erosion occurs at the outer bend, particularly during the rainy season.

The findings in relation to the flow velocity and SSC contradict the findings of previous studies performed by Tiron Duţu et al. (2014) and Dugué et al. (2013) with respect to meandering channel processes. The erosion at the outer bend should be more dominant than that at the inner bend due to centrifugal acceleration and channel resistance. However, the flow velocity and SSC exhibited opposite trends. The inner bend exhibited 4% higher sediment concentration, compared to that at the outer bend. This affected the magnitude of the flow velocity wherein the flow velocity at the inner bend was 35% higher than that at the outer bend. A reasonable explanation has been provided by the results for the turbulent flow region on the inner and outer bends, which suggests that the inner bend exhibits a higher correlation between the average flow velocity and Reynolds number, compared to that of the outer bend. However, the results of the study indicated the significance of the inner and outer bend flow conditions on river morphology changes. This is especially relevant for meandering segments. The curved channel changed periodically as a critical part of the river system, given changes in the flow force applied to the river bend and riverbed. This is illustrated by the three river cross-sections at the study site. Cross-section II (which is the centre of a curved segment) exhibited pool development at the outer bend because secondary flow existed in the stream bed area. The study suggests the potential change in the meandering segment by reviewing the fluctuation in flow parameters during two seasonal periods in alluvial rivers. In addition, the accumulation of suspended sediment in the depositional area that may change the river morphology is in line with a previous study conducted in the Porong River by Sidik et al. (2016). Sediment concentration and flow interaction can be used as predictors for morphological changes in alluvial rivers. Future studies should focus on strengthening the origin of changes in river morphology.

Data Availability Statement

Data sharing is not applicable to this article as no new data was created or analysed in this study.

References

Abate M., Nyssen J., Steenhuis T.S., Moges M.M., Tilahun S.A., Enku T. and Adgo E. (2015). Morphological changes of Gumara River channel over 50 years, upper Blue Nile Basin, Ethiopia. *Journal of Hydrology* , Vol. 525, pp. 152–164.

Alekseevskiy N.I., Berkovich K.M. and Chalov R.S. (2008). Erosion, sediment transportation and accumulation in rivers. *International Journal of Sediment Research* , Vol. 23, pp. 93–105.

Chanson H., Reungoat D., Simon B. and Lubin P. (2011). High-frequency turbulence and suspended sediment concentration measurements in the Garonne River tidal bore. *Estuarine, Coastal and Shelf Science* , Vol. 95, pp. 298–306.

Dingman S.L. (2009). "Fluvial Hydraulics", Oxford University Press. Inc., New York.

Dugué V., Blanckaert K., Chen Q. and Schleiss A.J. (2013). Reduction of bend scour with an air-bubble screen - morphology and flow patterns.*International Journal of Sediment Research* , Vol. 28, pp. 15–23. https://doi.org/10.1016/S1001-6279(13)60014-1

El Mountassir G., Sánchez M., Romero E. and Soemitro R.A.A. (2011). Behaviour of compacted silt used to construct flood embankment. Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, Vol. 164, pp. 195–210.

Gusarov A.V. (2020). The response of water flow, suspended sediment yield and erosion intensity to contemporary long-term changes in climate and land use/cover in river basins of the Middle Volga Region, European Russia. *Science of the Total Environment* , Vol. 719, 134770. https://doi.org/10.1016/j.scitotenv.2019.134770.

Higgins A., Restrepo J.C., Ortiz J.C., Pierini J. and Otero L. (2016). Suspended sediment transport in the Magdalena River (Colombia, South America): Hydrologic regime, rating parameters and effective discharge variability. *International Journal of Sediment Research* , Vol. 31, pp. 25-35.

Hoekstra P., Augustinus P.G.E.F. and Terwindt J.H.J. (1988). River outflow and mud deposition in a monsoon-dominated coastal environment. Physical Processes in Estuaries*, Springer-Verlag,* Berlin Heidelberg, pp. 311-331.

Juez C., Thalmann M., Schleiss A.J., Franca M.J. (2018). Morphological resilience to flow fluctuations of fine sediment deposits in bank lateral cavities. *Advances in Water Resources* , Vol. 115, pp. 44–59.

Jugaru Tiron L., Le Coz J., Provansal M., Panin N., Raccasi G., Dramais G. and Dussouillez P. (2009). Flow and sediment processes in a cutoff meander of the Danube Delta during episodic flooding. *Geomorphology* , Vol. 106, pp. 186–197.

Konsoer K.M., Rhoads B.L., Langendoen E.J., Best J.L., Ursic M.E., Abad J.D. and Garcia M.H. (2016). Spatial variability in bank resistance to erosion on a large meandering, mixed bedrock-alluvial river. *Geomorphology* , Vol. 252, pp. 80–97.

Liu J.H., Yang S.L., Zhu Q. and Zhang J. (2014). Controls on suspended sediment concentration profiles in the shallow and turbid Yangtze Estuary. *Continental Shelf Research* , Vol. 90, pp. 96–108.

Maulana M.A., Soemitro R.A.A., Mukunoki T. and Anwar N. (2018). Suspended sediment concentration assessment as a precursor to river channel shifting in the Bengawan Solo River, Indonesia. *Jurnal Teknologi,* Vol. 80, pp. 95–102.

Mouri G., Ros F.C. and Chalov S. (2014). Characteristics of suspended sediment and river discharge during the beginning of snowmelt in volcanically active mountainous environments. *Geomorphology* , Vol. 213, pp. 266–276.

Nadal-Romero E., Regüés D. and Latron J. (2008). Relationships among rainfall, runoff, and suspended sediment in a small catchment with badlands. *CATENA* , Vol. 74, pp. 127–136.

Reungoat D., Leng X. and Chanson H. (2019). Turbulence and suspended sediment processes in the Garonne River tidal bore in November 2016. *International Journal of Sediment Research* , Vol. 34, pp. 496–508.

Rinaldi M. and Darby S.E. (2007). 9 Modelling river-bank-erosion processes and mass failure mechanisms: progress towards fully coupled simulations. *Developments in Earth Surface Processes* , Vol. 11, pp. 213–239.

Rodríguez-Blanco M.L., Taboada-Castro M.M. and Taboada-Castro M.T. (2020). Suspended sediment dynamics during a period of consecutive explosive cyclogeneses in rural temperate catchments: A case study from small-sized catchments in NW Spain. *CATENA* , Vol. 187. https://doi.org/10.1016/j.catena.2019.104316.

Sidik F., Neil D. and Lovelock C.E. (2016). Effect of high sedimentation rates on surface sediment dynamics and mangrove growth in the Porong River, Indonesia. *Marine Pollution Bulletin* , Vol. 107, pp. 355–363.

Soemitro R.A.A. and Asmaranto R. (2016). The effect of drying - wetting cycles to the Wischmeier soil erodibility factors. *Proc. of the 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Japanese Geotechnical Society Special Publication* , Vol. 2, pp. 595–598. http://doi.org/10.3208/jgssp.INA-06.

Tiron Duţu L., Provansal M., Le Coz J. and Duţu F. (2014). Contrasted sediment processes and morphological adjustments in three successive cutoff meanders of the Danube delta. *Geomorphology* , Vol. 204, pp. 154–164.

Uddin M.N. and Rahman M.M. (2012). Flow and erosion at a bend in the braided Jamuna River. *International Journal of Sediment Research* , Vol. 27, pp. 498–509.

Unverricht D., Nguyen T.C., Heinrich C., Szczuciński W., Lahajnar N. and Stattegger K. (2014). Suspended sediment dynamics during the inter-monsoon season in the subaqueous Mekong Delta and adjacent shelf, southern Vietnam. *Journal of Asian Earth Sciences* , Vol. 79, pp. 509–519.

Wang J.J. and Lu X.X. (2010). Estimation of suspended sediment concentrations using Terra MODIS: An example from the Lower Yangtze River, China. *Science of the Total Environment,* Vol. 408, pp. 1131–1138.

Hosted file

`201127 Figure_River research and applications.docx` available at https://authorea.com/users/501628/articles/581987-morphology-changes-affected-by-sediment-concentration-and-river-flow-in-meandering-channels-of-the-bengawan-solo-river